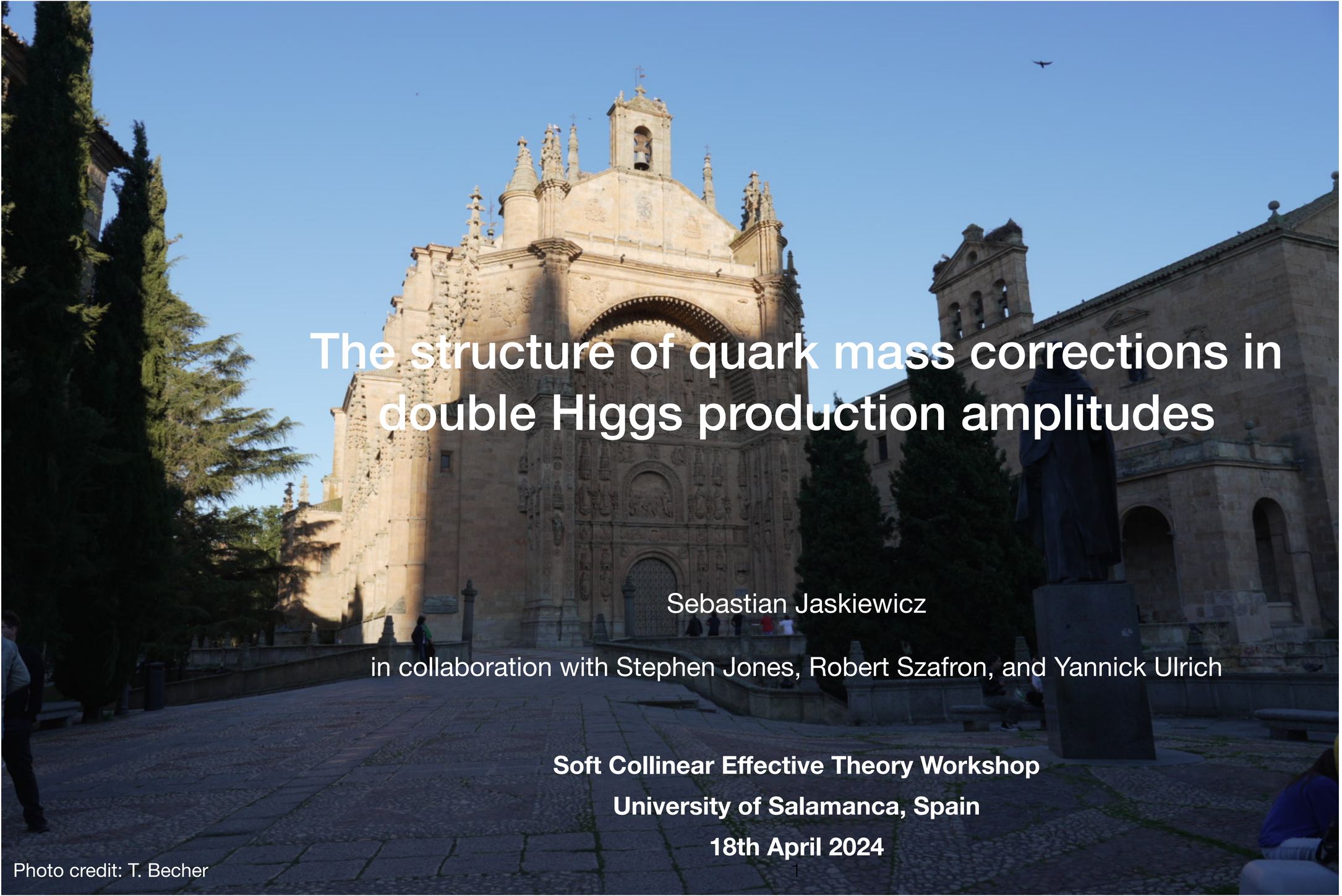

The structure of quark mass corrections in double Higgs production amplitudes

Sebastian Jaskiewicz

in collaboration with Stephen Jones, Robert Szafron, and Yannick Ulrich

Soft Collinear Effective Theory Workshop

University of Salamanca, Spain

18th April 2024

Photo credit: T. Becher

b
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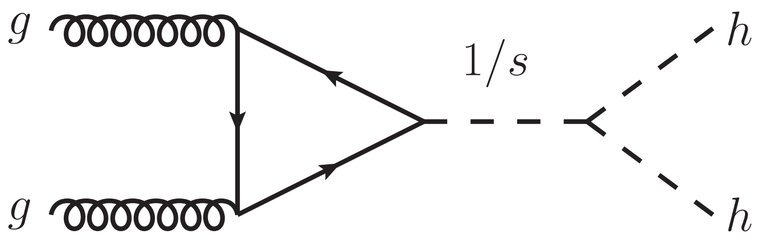
FOR FUNDAMENTAL PHYSICS

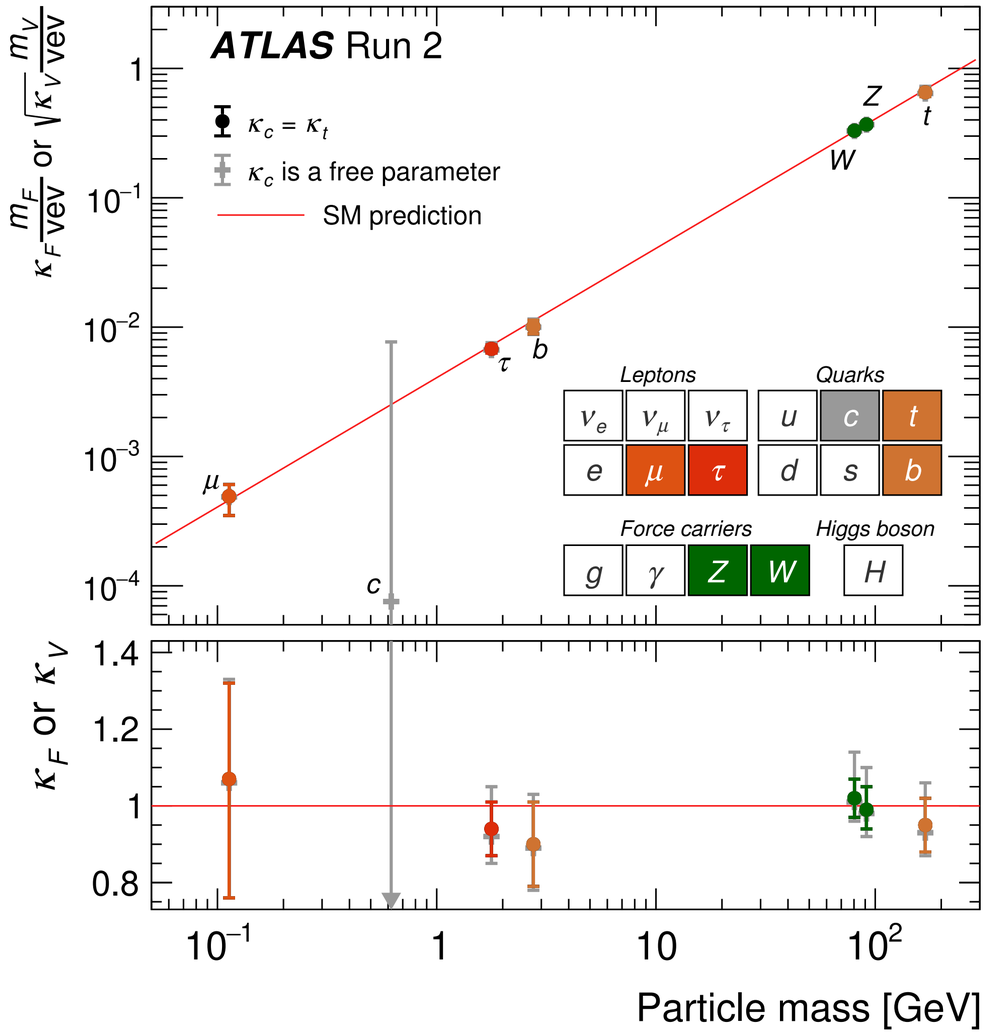
Higgs couplings

- Top-quark Yukawa coupling first directly observed in 2018 ($t\bar{t}H$)
  [ATLAS Collaboration, 1806.00425] [CMS Collaboration, 1804.02610]
- Higgs coupling to second generation leptons measured in 2020 ($H \to \mu^+\mu^-$)
  [ATLAS Collaboration, 2007.07830] [CMS Collaboration, 2009.04363]
- Higgs coupling to second generation quarks measured in 2022 ($H \to c\bar{c}$)
  [ATLAS Collaboration, 2201.11428] [CMS Collaboration, 2205.05550]

- The Higgs self-coupling is yet to be measured

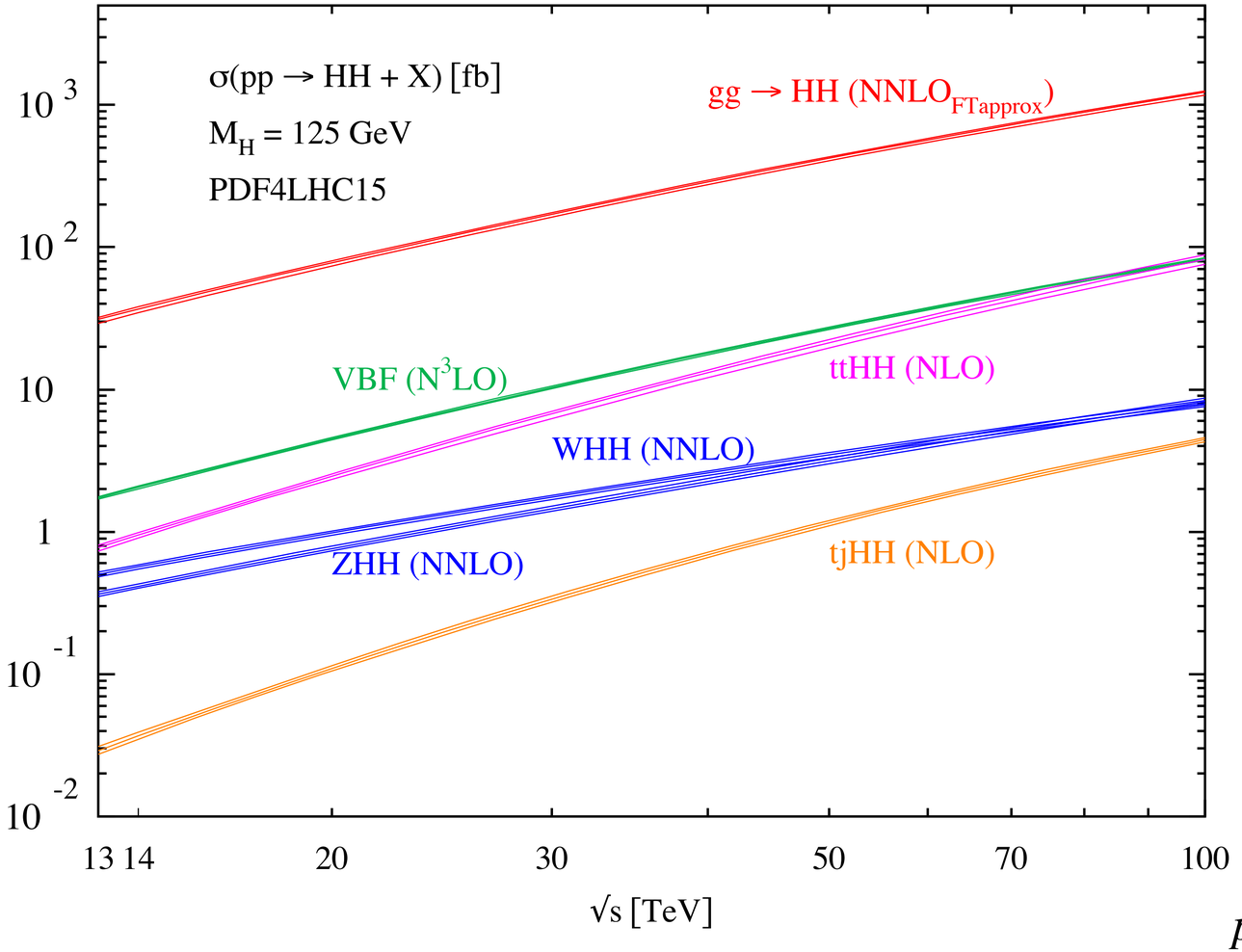
$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4 \qquad m_H^2 = 2\lambda v^2$$



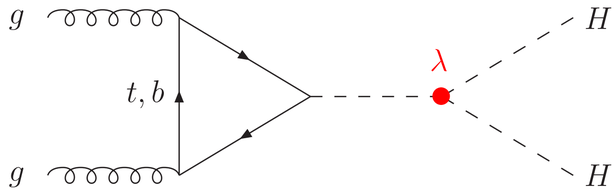


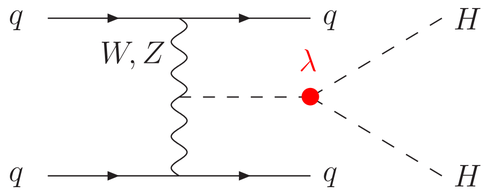
[ATLAS Collaboration, CERN-EP-2022-057, 2207.00092]

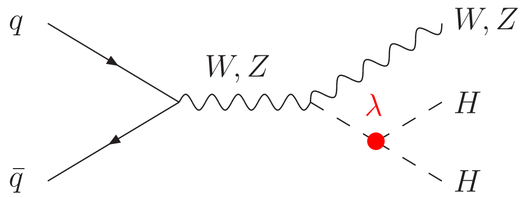
Double Higgs production

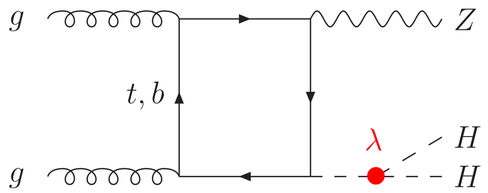


[LHCHXSWG-2019-005, 1910.00012]

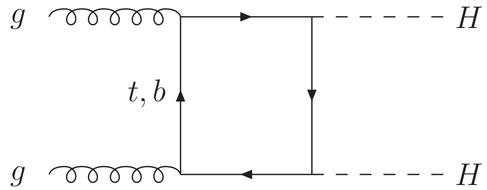






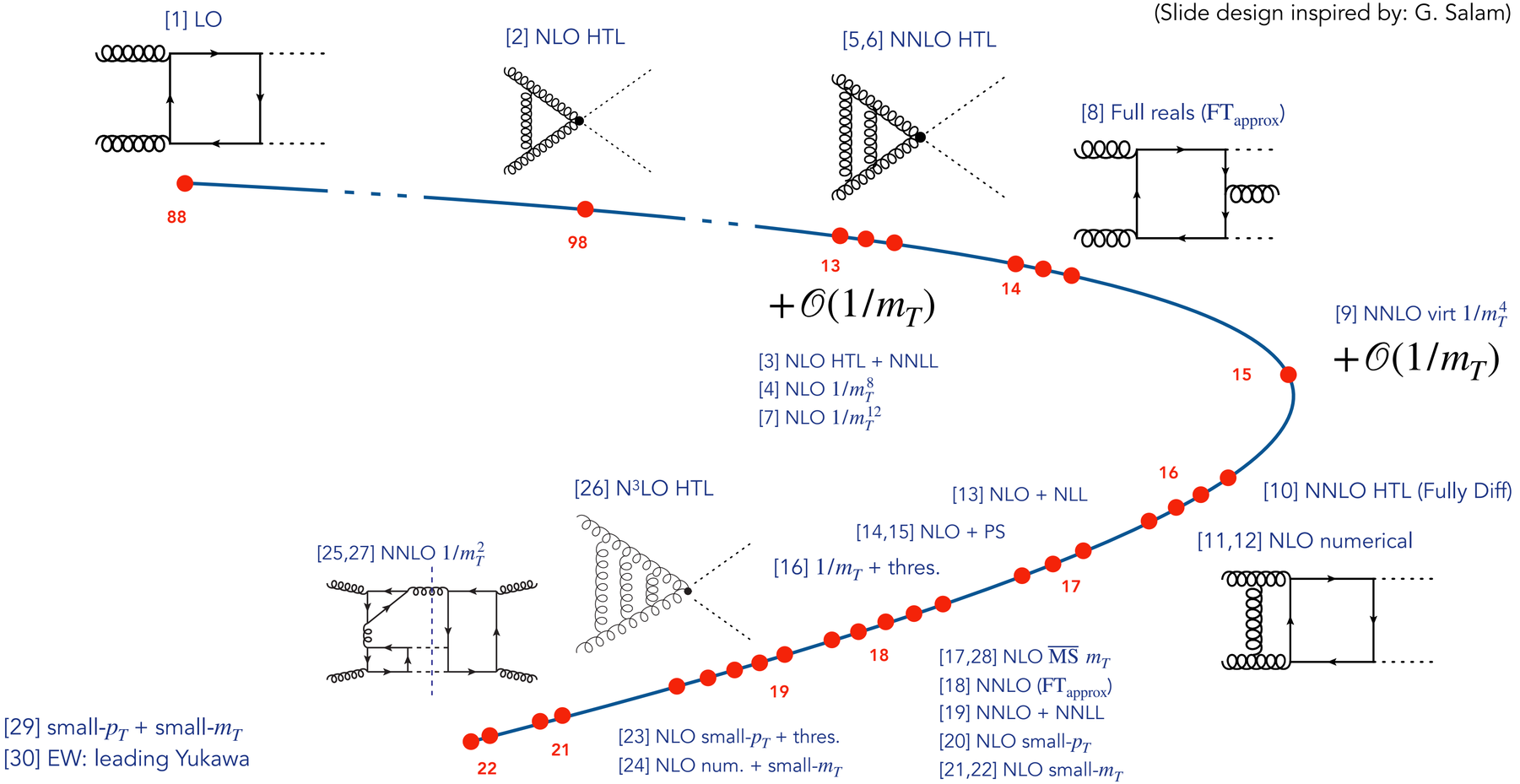


The cross-section for $pp \to HH$ process is a factor 1000 smaller than $pp \to H$ production cross-section



Gluon fusion: theory overview

(Slide design inspired by: G. Salam)



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, Jones, Kerner, Luisoni, Vryonidou 17; [15] Jones, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, Jones, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22;

(Slide borrowed from S. Jones)

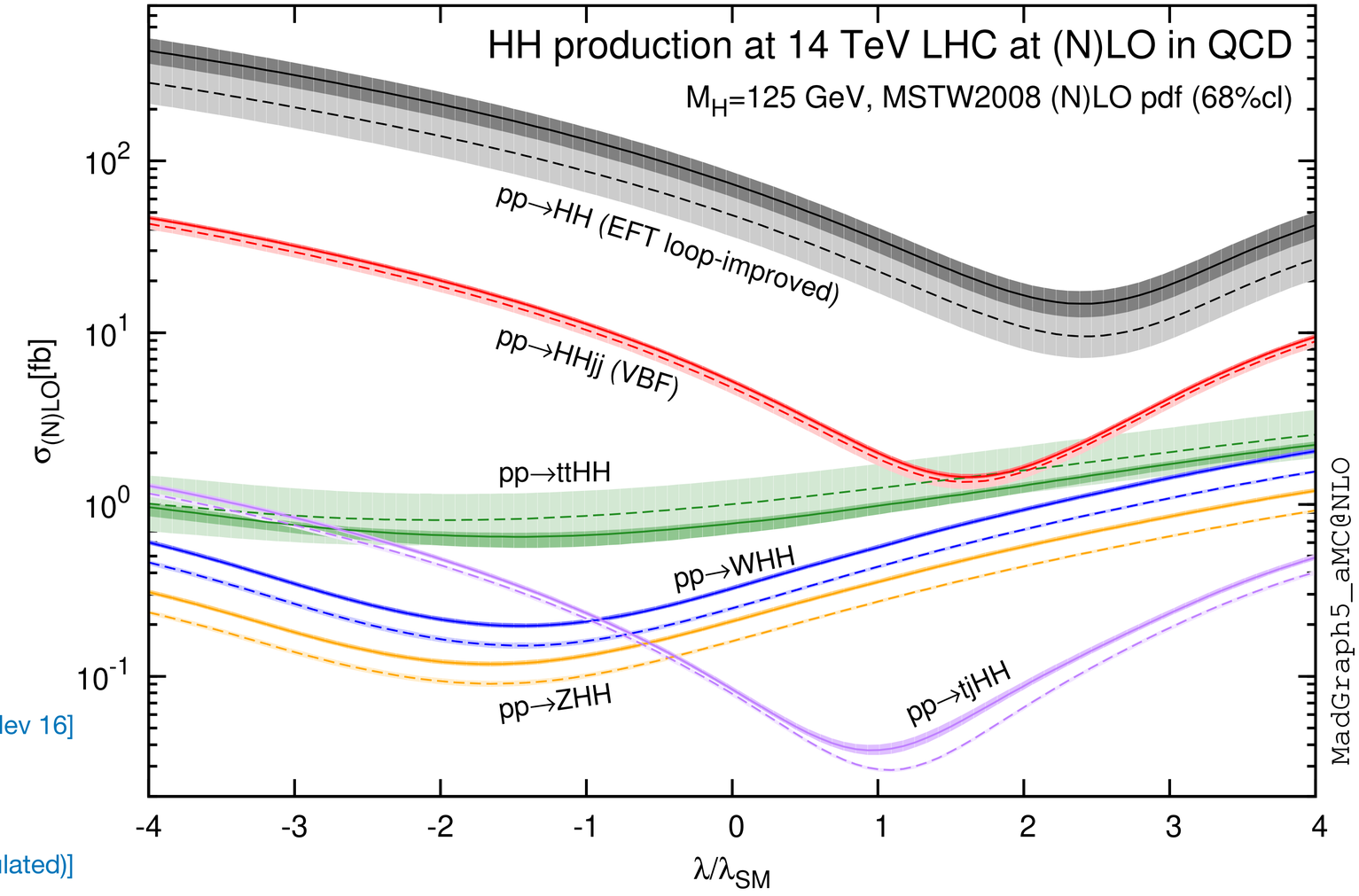
Scale uncertainty

Combination of NLO and N^{m}LO HTL yields:

- Scale uncertainty of: $+2\,\%$ / $-5\,\%$

- PDF $+\alpha_s$: $\pm 3.0\,\%$

- m_T approx: $\pm 2.7\,\%$



[Chen, Li, Shao, Wang 19, 19]

[Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli 18;]

[de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16]

[Maltoni, Vryonidou, Zaro 14 (recalculated);]

[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 16]

[Dawson, Dittmaier, Spira 98 (recalculated); Glover, van der Bij 88 (recalculated)]

[R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, and M. Zaro, 1401.7340]

[J. Baglio, A. Djouadi, R. Gröber, M. M. Mühlleitner, J. Quevillon, and M. Spira, 1212.5581]

Mass scheme uncertainties

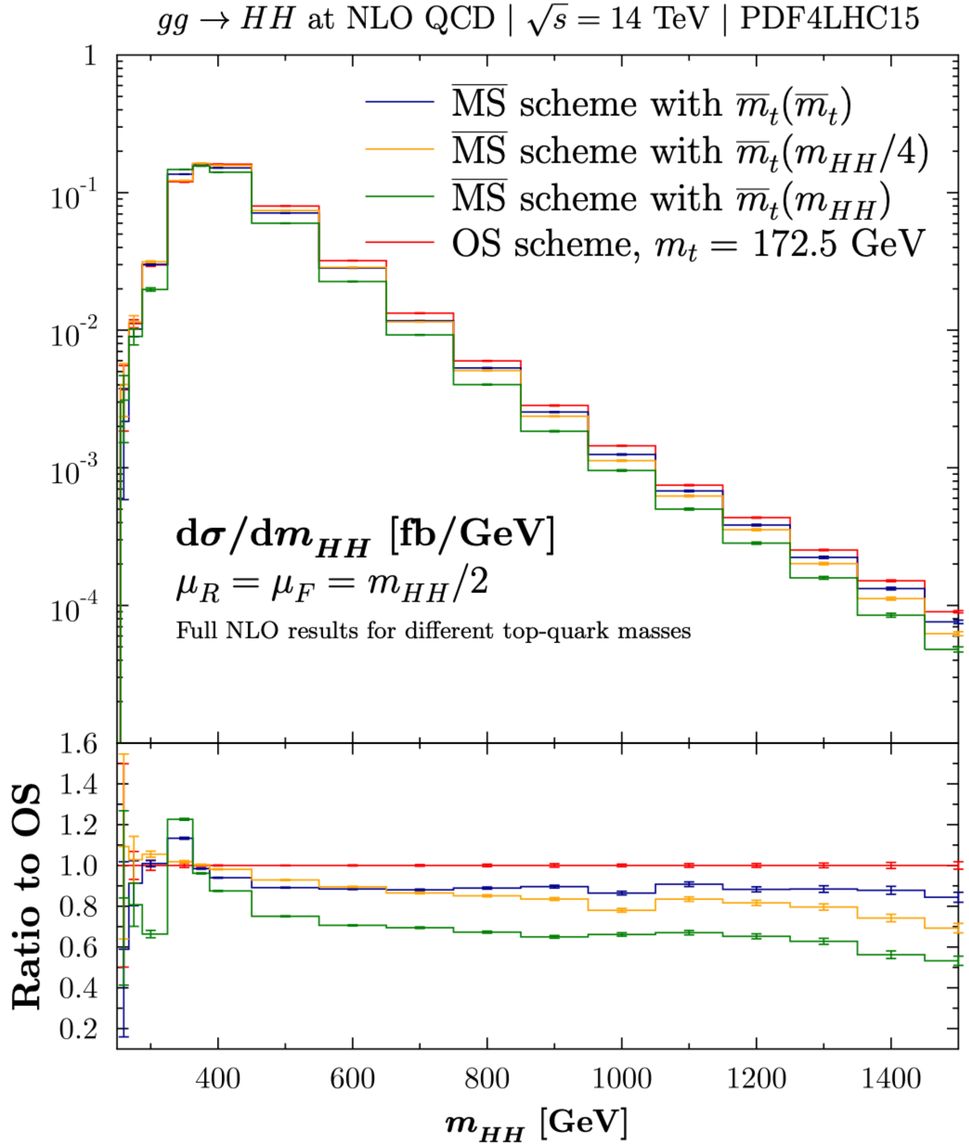
Converting the top quark mass to the $\overline{\text{MS}}$ scheme

$$m_t \to \overline{m}_t(\mu_t)\left(1+\frac{\alpha_s(\mu_R)}{4\pi}C_F\left\{4+3\log\left[\frac{\mu_t^2}{\bar{m}_t(\mu_t)^2}\right]\right\}\right)$$

This leads to an addition uncertainty related to the choice of the top-quark mass scheme

$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%} \text{ fb},$$
$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%} \text{ fb},$$

[J. Baglio, F. Campanario, S. Glaus, M. Muehlleitner, J. Ronca, M. Spira, J. Streicher, 2003.03227, 2008.11626]



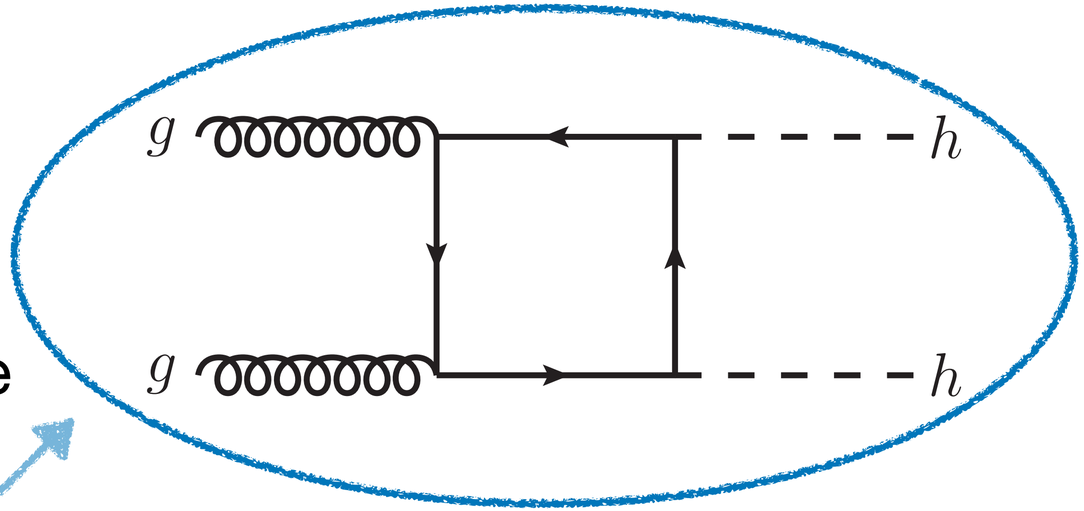
$gg \to hh$ amplitudes

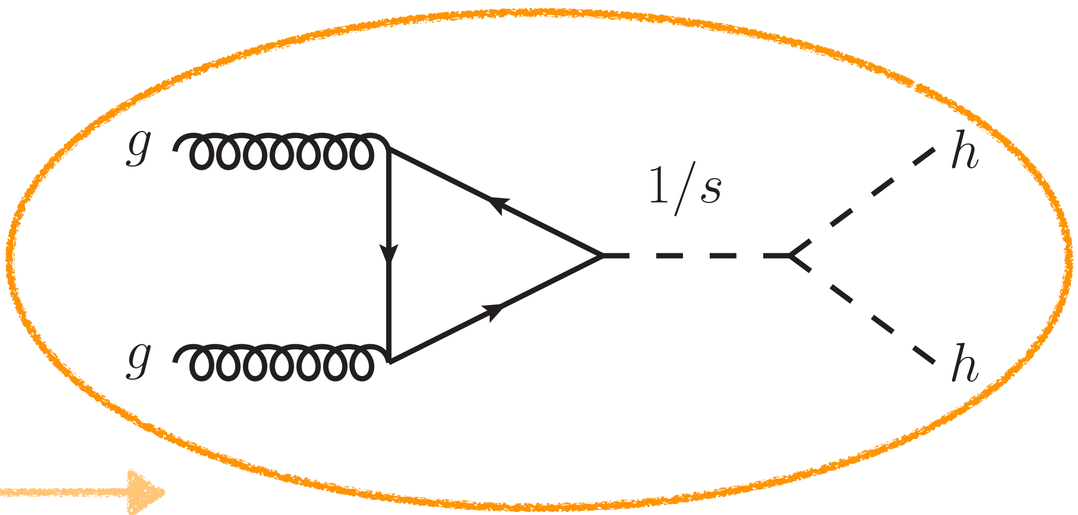
Structure of QCD corrections in the amplitude

$$\mathscr{M} = \varepsilon_{1,\mu}\,\varepsilon_{2,\nu}\,\delta^{AB}\left(A_1 P_1^{\mu\nu} + A_2 P_2^{\mu\nu}\right)$$

$$A_1 = T_F \frac{G_F}{\sqrt{2}} \frac{\alpha_s}{2\pi} s \left[\frac{3m_H^2}{s - m_H^2} A_{1,y_t\lambda} + A_{1,y_t^2}\right]$$

$$A_2 = T_F \frac{G_F}{\sqrt{2}} \frac{\alpha_s}{2\pi} s \left[A_{2,y_t^2}\right]$$





$$P_1^{\mu\nu} = g^{\mu\nu} - \frac{n_{1-}^{\nu} n_{2-}^{\mu}}{n_{1-} \cdot n_{2-}}$$

$$P_2^{\mu\nu} = g^{\mu\nu} + \frac{n_{1-} \cdot n_{2-}\, n_{3-}^{\nu} n_{3-}^{\mu}}{n_{1-} \cdot n_{3-}\; n_{2-} \cdot n_{3-}} - \frac{n_{1-}^{\nu} n_{3-}^{\mu}}{n_{1-} \cdot n_{3-}} - \frac{n_{3-}^{\nu} n_{2-}^{\mu}}{n_{3-} \cdot n_{2-}}$$

High-energy limit

$$s, |t|, |u| \gg m_t^2 \gg m_H^2$$

$gg \to hh$

[J. Davies, G. Mishima, M. Steinhauser, D. Wellmann, 1811.05489]

[J. Baglio, F. Campanario, S. Glaus, M. Muehlleitner, J. Ronca, M. Spira, J. Streicher, 2008.11626]

$$A^{(0)}_{i,y_t^2} = y_t^2\, f_i(s,t) + y_t^2\, \mathcal{O}(m_t^2)$$

$$A^{(1)}_{i,y_t^2} = 6C_F\, A_i^{(0)}\, \log\left[\frac{m_t^2}{s}\right] + y_t^2\, \mathcal{O}(m_t^2)$$

For $gg \to hh$, the leading logarithm in m_t^2 comes from the mass counter term. In $\overline{\text{MS}}$, this is converted to $\log[\mu_t^2/s]$ → choose scale $\mu_t^2 \sim s$

$gg \to Zh$

[J. Davies, G. Mishima, M. Steinhauser, 20]

[Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser, 22]

$$A_i^{(0)} = y_t^2\, f_i(s,t) \log^2\left[\frac{m_t^2}{s}\right] + y_t^2\, \mathcal{O}(m_t^2)$$

$$A_i^{(1)} = \frac{(C_F - C_A)}{6}\, A_i^{(0)}\, \log^2\left[\frac{m_t^2}{s}\right] + y_t^2\, \mathcal{O}(m_t^2)$$

Similar power suppressed mass logarithms studied for single Higgs

[Liu, Penin 18; Anastasiou, Penin 20; Liu, Modi, Penin 22; Liu, Neubert, Schnubel, Wang 22]

Method of regions

- Perform expansion by regions with pySecDec.

[M. Beneke, V. Smirnov, hep/9711391]

[G. Heinrich, S. Jahn, S. Jones, M. Kerner, F. Langer, V. Magerya, A. Poldaru, J. Schlenk, E. Villa, 2108.10807]

- Utilises the geometric approach

[A. Pak, A. Smirnov, 1011.4863]

- Regions obtained from lower facets of the Newton polytope constructed from the Lee-Pomeransky polynomial

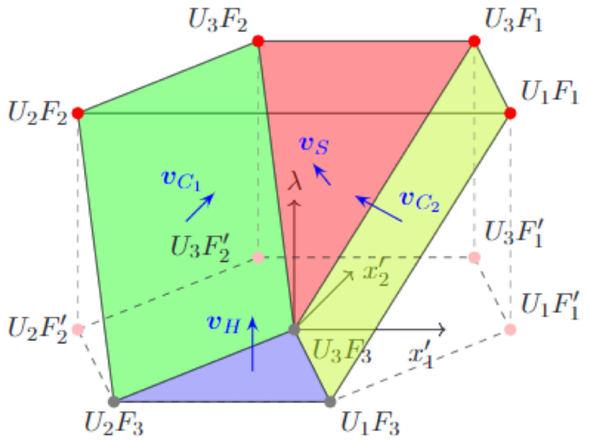
[B. Jantzen, A. Smirnov, V. Smirnov, 1206.0546]

[See talk by Y. Ma on Wednesday]

Identifying regions from Newton polytopes

- There have been computer codes based on this approach:

  Asy2, ASPIRE, pySecDec, …



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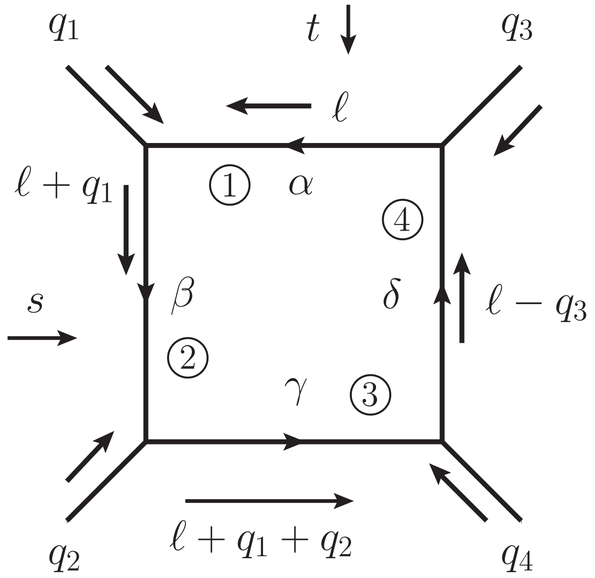
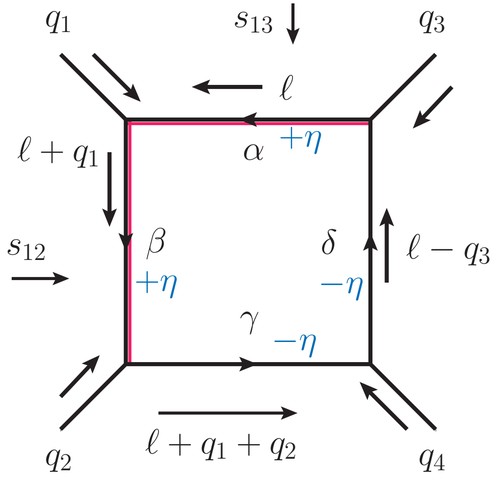
- Lee-Pomeransky representation of Feynman integrals gives region vectors corresponding to scaling of propagators. [1308.6676]
- Rapidity divergences in the collinear regions -these require additional regulator

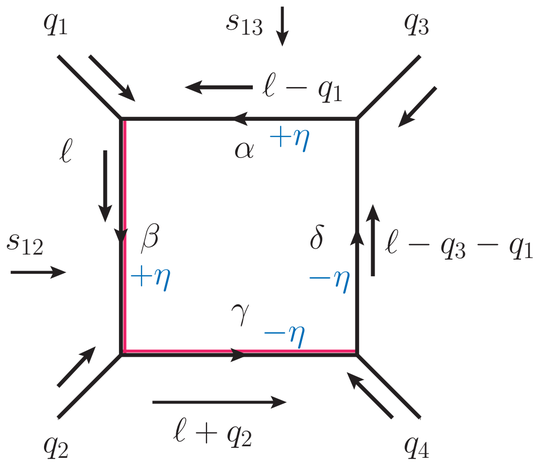
Hard region

$\mathbf{u}^{(0)} = (0,0,0,0)$

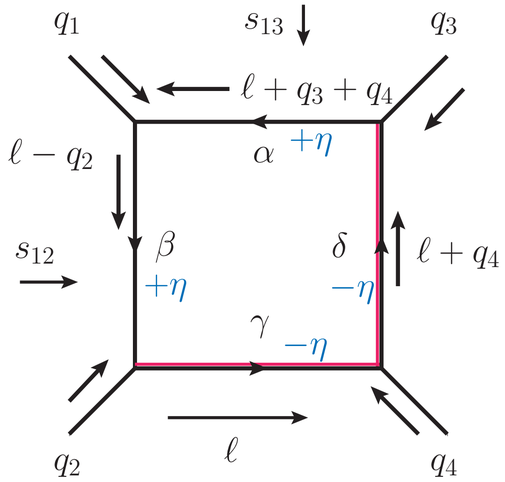




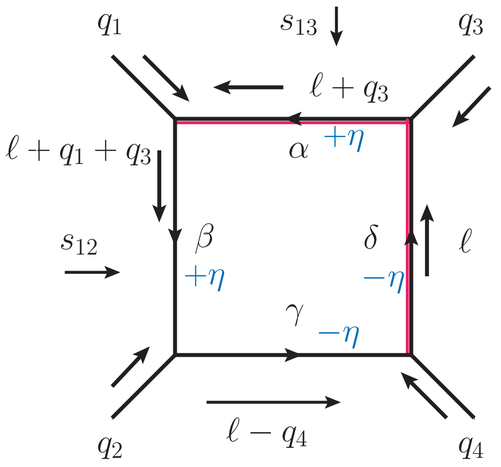
$\mathbf{u}^{(1)} = (-2,-2,0,0)$



$\mathbf{u}^{(2)} = (0,-2,-2,0)$



$\mathbf{u}^{(4)} = (0,0,-2,-2)$



$\mathbf{u}^{(3)} = (-2,0,0,-2)$

Method of regions

- Perform expansion by regions with pySecDec.

[M. Beneke, V. Smirnov, hep/9711391]

[G. Heinrich, S. Jahn, S. Jones, M. Kerner, F. Langer, V. Magerya, A. Poldaru, J. Schlenk, E. Villa, 2108.10807]

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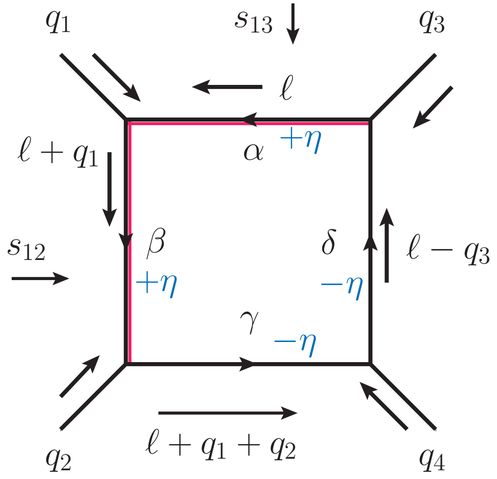
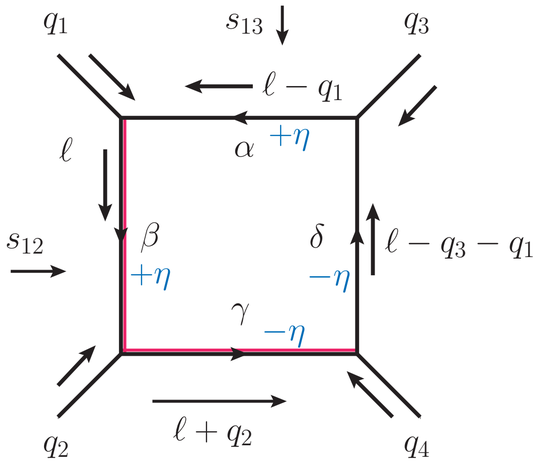


$$\mathbf{u}^{(1)} = (-2,-2,0,0)$$



$$\mathbf{u}^{(2)} = (0,-2,-2,0)$$

Hard region

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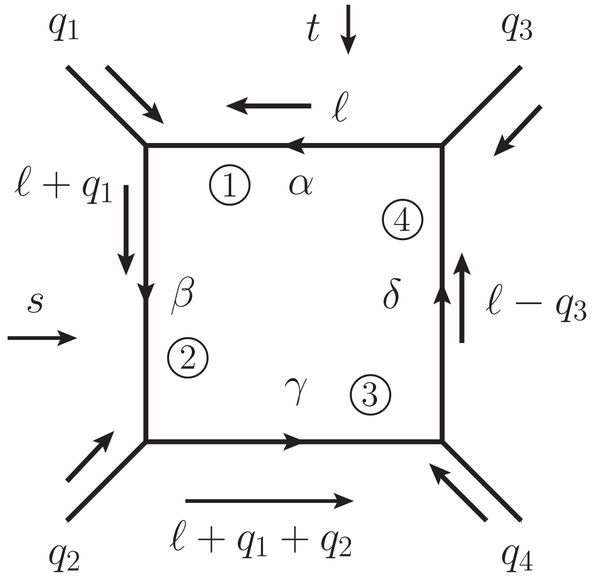

$$\int \underbrace{\frac{d^d\ell}{(2\pi)^d}}_{\lambda^4} \underbrace{\frac{1}{\ell^2-m_t^2}}_{\frac{1}{\lambda^2}} \underbrace{\frac{1}{(\ell+q_1)^2-m_t^2}}_{\frac{1}{\lambda^2}} \frac{1}{2(\ell+q_1)\cdot q_2} \frac{1}{-2\ell\cdot q_3}$$

Method of regions

- Perform expansion by regions with pySecDec.

[M. Beneke, V. Smirnov, hep/9711391]

[G. Heinrich, S. Jahn, S. Jones, M. Kerner, F. Langer, V. Magerya, A. Poldaru, J. Schlenk, E. Villa, 2108.10807]

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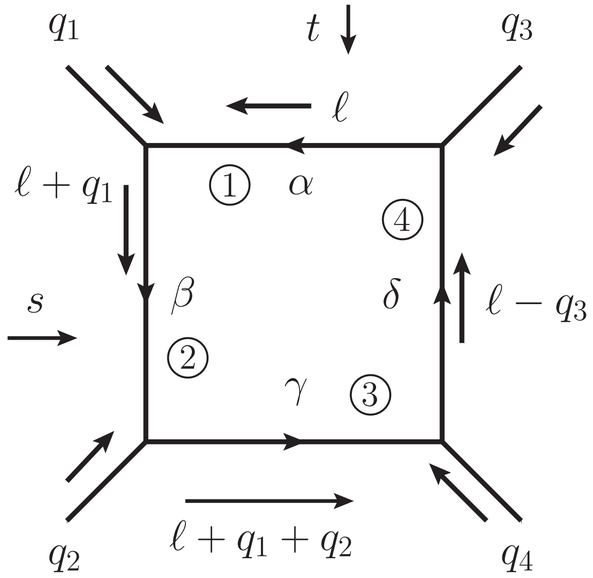

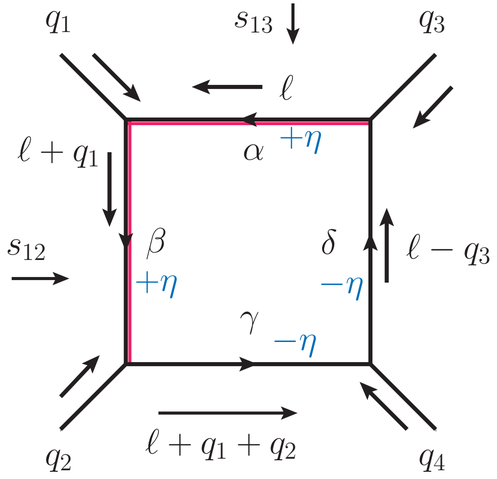

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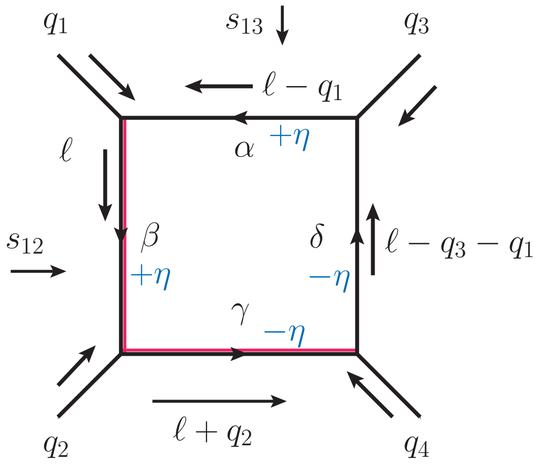


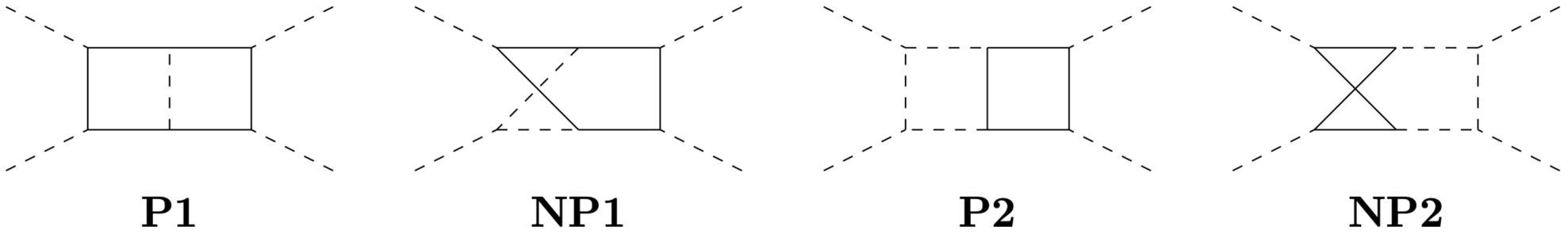
$\mathbf{u}^{(2)} = (0,-2,-2,0)$

Takeaway

- Scalar integrals all contributing at leading power
- Computing the amplitudes: - hard region reproduces the full leading power amplitude, collinear regions suppressed.
- Also true at integrand level!

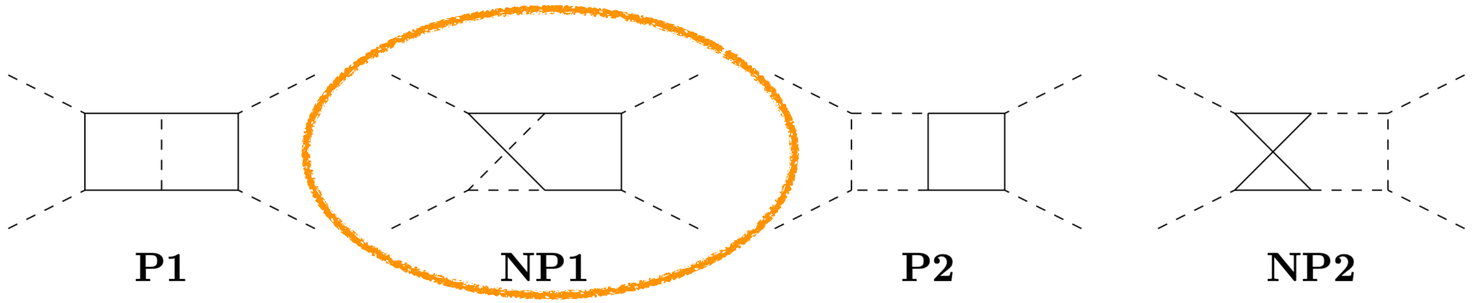
MoR: two-loop

At the two-loop order we have the following topologies

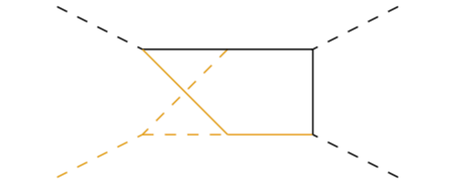


MoR: two-loop

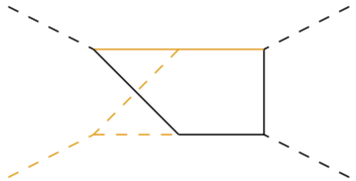
Consider the first non-planar topology NP1



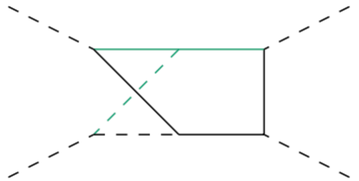
We find the following contributing regions



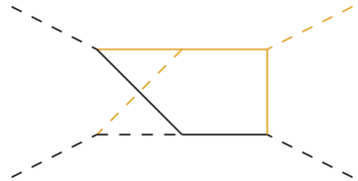
$(-2,-2,-2,0,0,0,-2)$



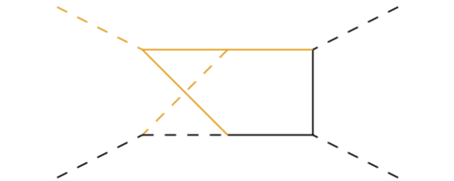
$(-2,-2,0,0,-2,-2,0)$



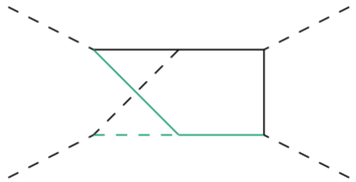
$(-2,-1,0,-1,-2,-2,-1)$



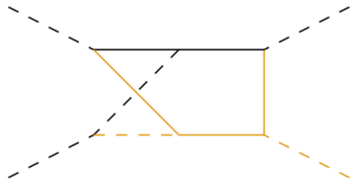
$(-2,0,0,-2,-2,-2,0)$



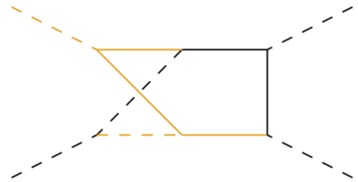
$(-2,0,0,0,-2,-2,-2)$



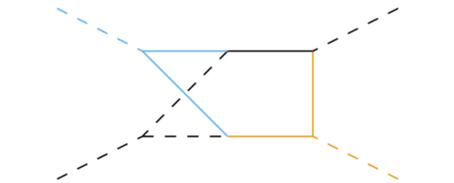
$(-1,-2,-2,-1,0,-1,-2)$



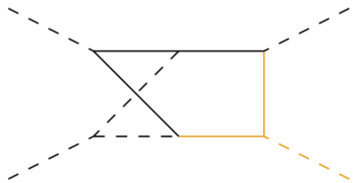
$(0,-2,-2,-2,0,0,-2)$



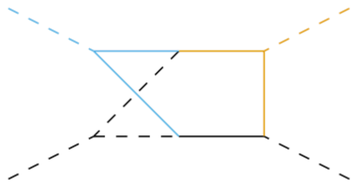
$(0,-2,-2,0,0,-2,-2)$



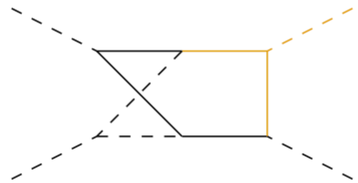
$(0,0,-2,-2,0,-2,-2)$



$(0,0,-2,-2,0,0,0)$



$(0,0,0,-2,-2,-2,-2)$

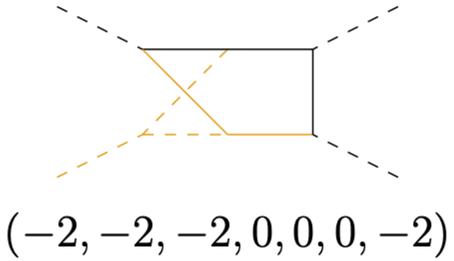


$(0,0,0,-2,-2,0,0)$

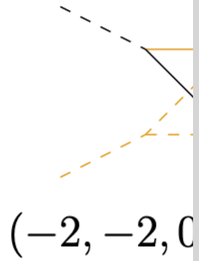
MoR: two-loop

Consider the first non-planar topology NP1

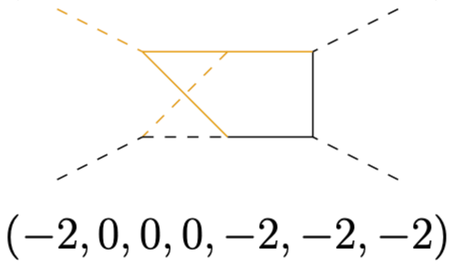
We find the following contributing regions



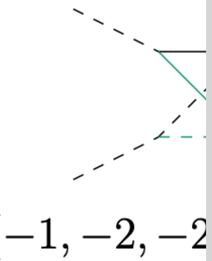
$(-2,-2,-2,0,0,0,-2)$



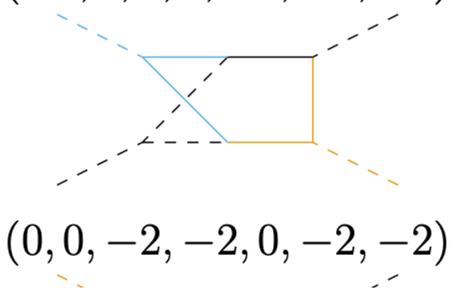
$(-2,-2,0$



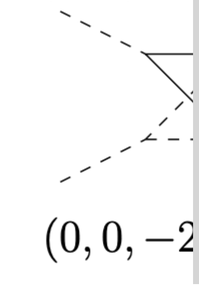
$(-2,0,0,0,-2,-2,-2)$



$(-1,-2,-2$



$(0,0,-2,-2,0,-2,-2)$

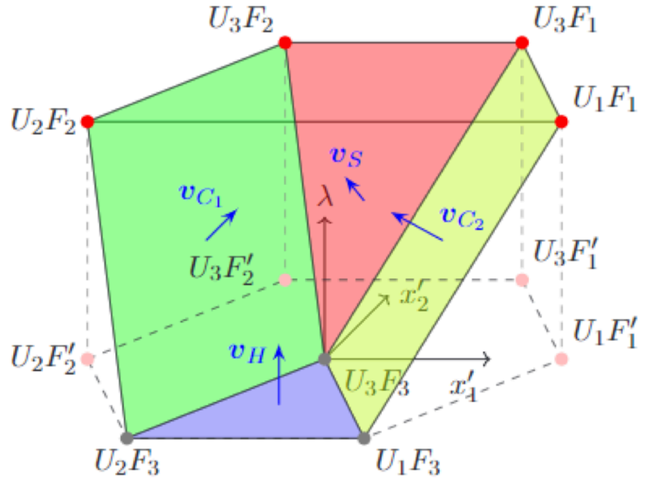


$(0,0,-2$

Identifying regions from Newton polytopes

- There have been computer codes based on this approach:

  Asy2, ASPIRE, pySecDec, …



- Timely results may not be available if the graph is not too simple.

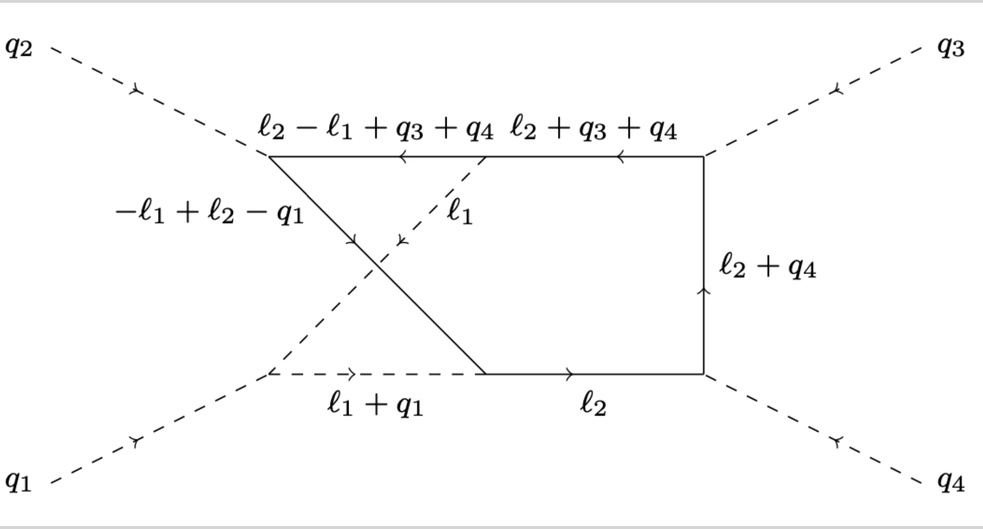
  Note that dim(polytope) = #(propagators)+1.

- Also, how to interpret the output in momentum space?

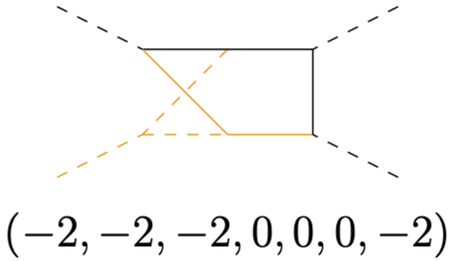
[See talk by Y. Ma on Wednesday]

MoR: two-loop

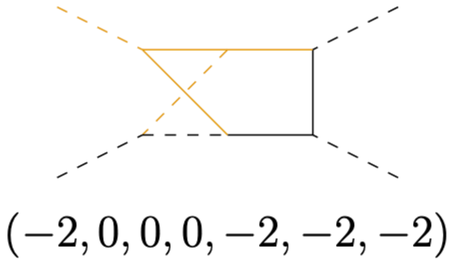
Consider the first non-planar topology NP1



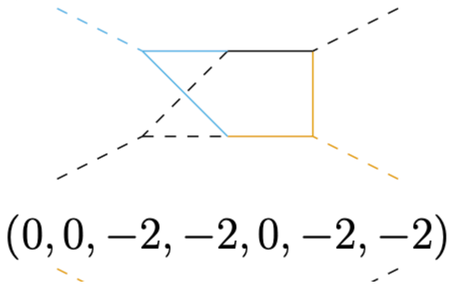
We find the following contributing regions



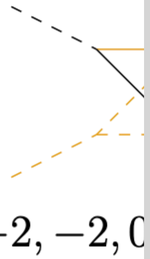
$(-2,-2,-2,0,0,0,-2)$



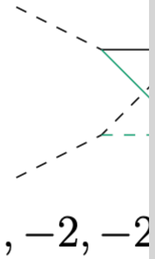
$(-2,0,0,0,-2,-2,-2)$



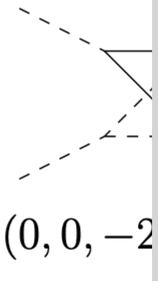
$(0,0,-2,-2,0,-2,-2)$



$(-2,-2,0$



$(-1,-2,-2$



$(0,0,-2$

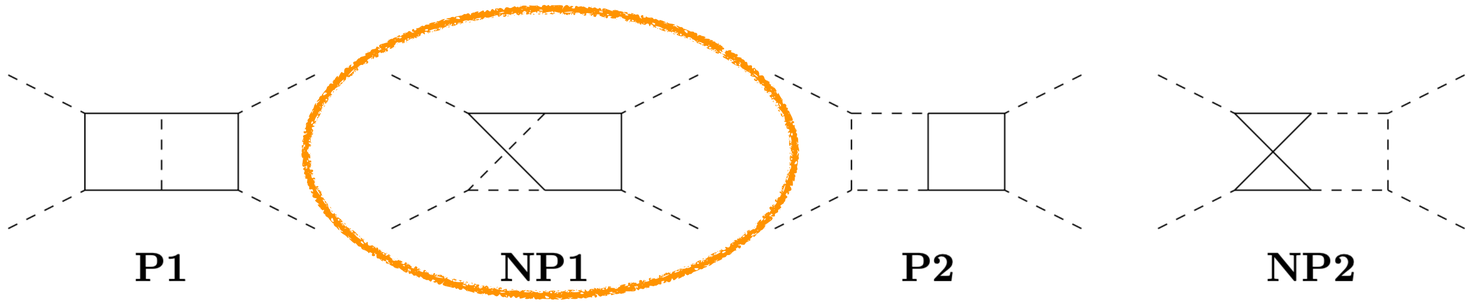
Code for translating to momentum space to be integrated in PySecDec

[S. Jones, Y. Ulrich, to appear]

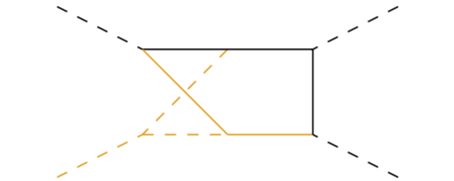
$\mathbf{u}^R$	order	interpretation	routing
(-2,-2,-2,0,0,0,-2)	-4ϵ	c_1c_1	ℓ_1, ℓ_2
(-2,-2,0,0,-2,-2,0)	-4ϵ	c_1c_1	ℓ_1, $\ell_2 - q_3 - q_4$
(-2,-1,0,-1,-2,-2,-1)	$-1-4\epsilon$	ss	ℓ_1, $\ell_2 - q_3 - q_4$
(-2,0,0,-2,-2,-2,0)	-4ϵ	c_3c_3	ℓ_1, $\ell_2 - q_4$
(-2,0,0,0,-2,-2,-2)	-4ϵ	c_2c_2	ℓ_1, $\ell_2 - q_3 - q_4$
(-1,-2,-2,-1,0,-1,-2)	$-1-4\epsilon$	ss	$\ell_1 - q_1$, ℓ_2
(0,-2,-2,-2,0,0,-2)	-4ϵ	c_4c_4	$\ell_1 - q_1$, ℓ_2
(0,-2,-2,0,0,-2,-2)	-4ϵ	c_2c_2	$\ell_1 - q_1$, ℓ_2
(0,0,-2,-2,0,-2,-2)	-4ϵ	$c_4\bar{c}_2$	$\ell_1 - \ell_2 + q_3 + q_4$, ℓ_1
(0,0,-2,-2,0,0,0)	-2ϵ	c_4h	$\ell_1 - \ell_2 + q_3 + q_4$, ℓ_1
(0,0,0,-2,-2,-2,-2)	-4ϵ	$c_3\bar{c}_2$	$\ell_1 - \ell_2 + q_3$, $\ell_1 - q_4$

MoR: two-loop

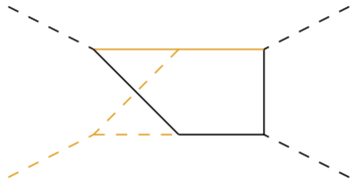
Consider the first non-planar topology NP1



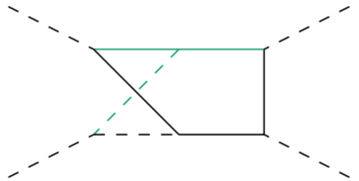
We find the following contributing regions



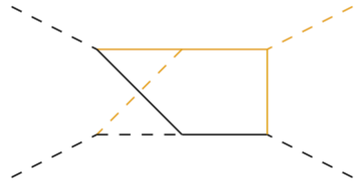
$(-2,-2,-2,0,0,0,-2)$



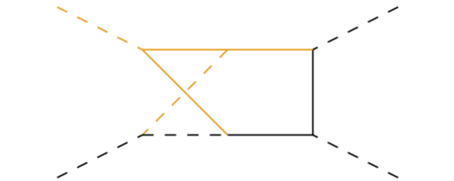
$(-2,-2,0,0,-2,-2,0)$



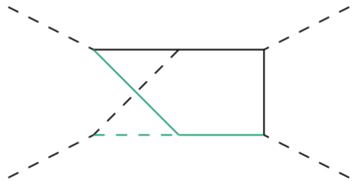
$(-2,-1,0,-1,-2,-2,-1)$



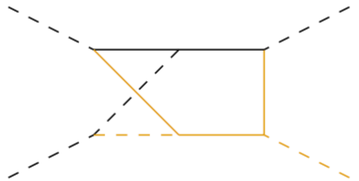
$(-2,0,0,-2,-2,-2,0)$



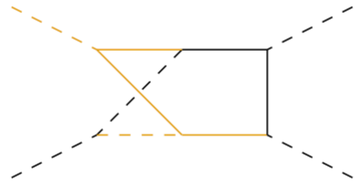
$(-2,0,0,0,-2,-2,-2)$



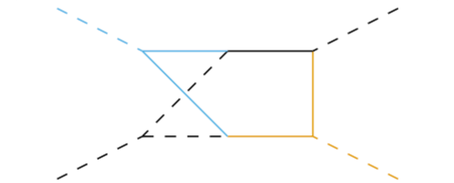
$(-1,-2,-2,-1,0,-1,-2)$



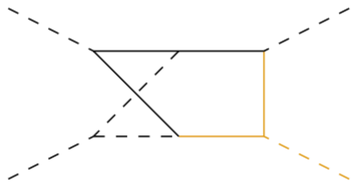
$(0,-2,-2,-2,0,0,-2)$



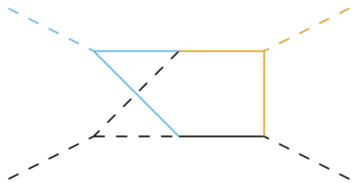
$(0,-2,-2,0,0,-2,-2)$



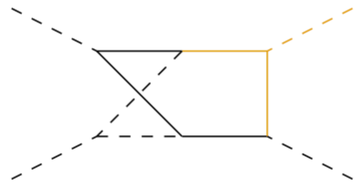
$(0,0,-2,-2,0,-2,-2)$



$(0,0,-2,-2,0,0,0)$



$(0,0,0,-2,-2,-2,-2)$

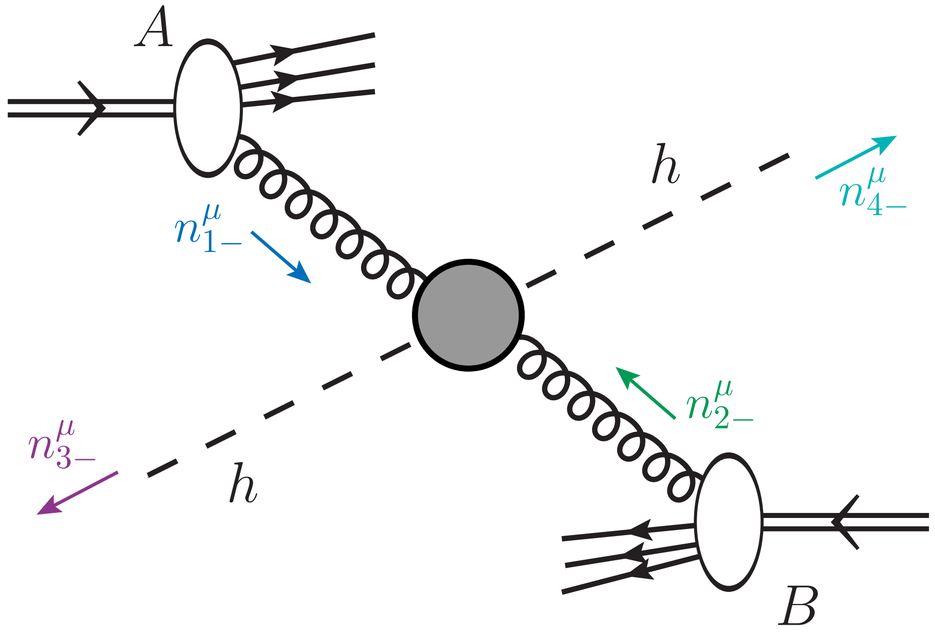


$(0,0,0,-2,-2,0,0)$

Effective field theory

[C. Bauer, S. Fleming, D. Pirjol and I. Stewart, hep-ph/0011336] [C. Bauer, D. Pirjol, I. Stewart, hep-ph/0109045]
[M. Beneke, A. Chapovsky, M. Diehl, T. Feldmann, hep-ph/0206152][M. Beneke, T. Feldmann, hep-ph//0211358]

$$\mathscr{L}_{\rm SCET} = \sum_{i=1}^{N} \mathscr{L}_{c_i} + \mathscr{L}_{\rm soft} \qquad \mathscr{L}_{c_i} = \underbrace{\mathscr{L}_{c_i}^{(0)}}_{\rm LP} + \underbrace{\mathscr{L}_{c_i}^{(1)}}_{\mathcal{O}(\lambda^1)} + \underbrace{\mathscr{L}_{c_i}^{(2)}}_{\mathcal{O}(\lambda^2)} + \dots$$

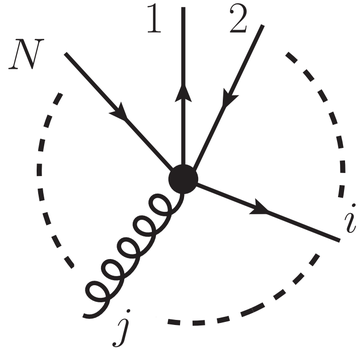


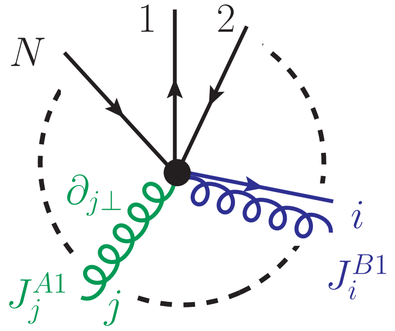
Subleading power operator basis for N-jets. Building blocks given by (up to $\mathcal{O}(\lambda^2)$):

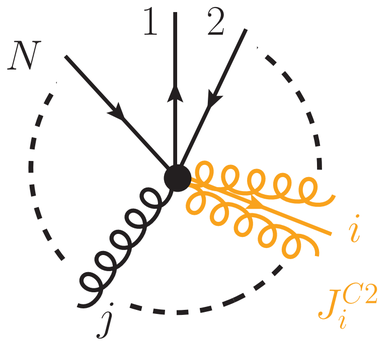
$$\chi_i(t_i n_{i+}) \equiv W_i^\dagger \, \xi_i \qquad \mathscr{A}_{i\perp}^{\mu}(t_i n_{i+}) \equiv W_i^\dagger [iD_{\perp i}^{\mu} \, W_i]$$

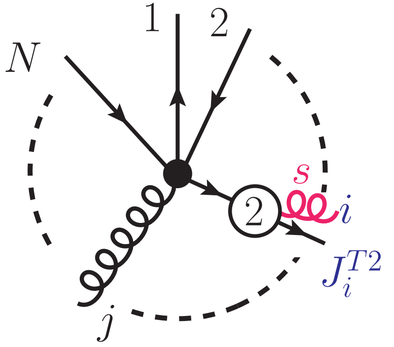
[D. Kolodrubetz, I. Moult, I. Stewart, 1601.02607] [I. Moult, I. Stewart, G. Vita, 1703.03408]
[I. Feige, D. Kolodrubetz, I. Moult, I. Stewart, G. Vita, 1703.0341]
[M. Beneke, M. Garny, R. Szafron, J. Wang, 1712.04416, 1712.07462, 1808.04742, 1907.05463]

$$\psi(x) \to \underbrace{\psi_1(x)+\dots+\psi_N(x)}_{N\,\text{collinear fermion fields}} + q(x)$$

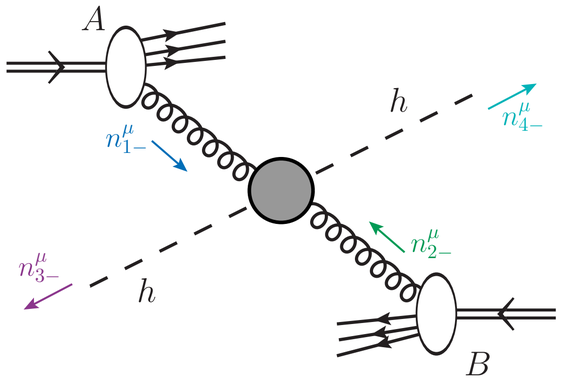






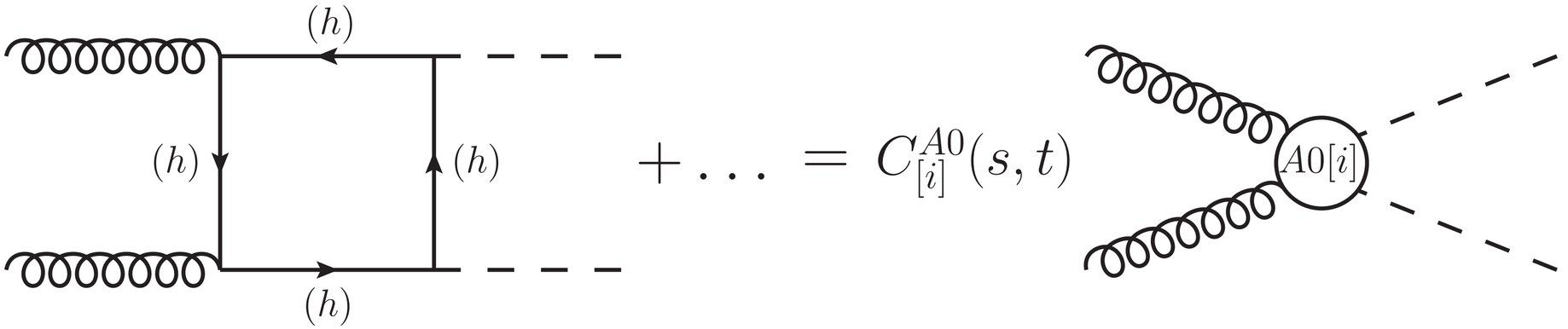


Hard scale $\mu^2 \sim s$



- Matching at the leading power

$$J^{[i]}_{\rm LP}(t_1,t_2,t_3,t_4) = y_t^2\, P_i^{\mu\nu}\ \mathscr{A}_{c_1\perp_1\,\mu}(t_1 n_{1+})\,\mathscr{A}_{c_2\perp_2\,\nu}(t_2 n_{2+})\ h_{c_3}(t_3 n_{3+})\ h_{c_4}(t_4 n_{4+})$$

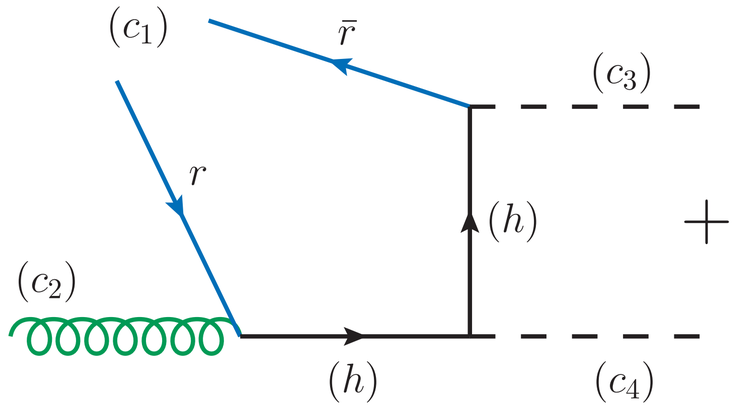


$$P_1^{\mu\nu} = g^{\mu\nu} - \frac{n_{1-}^\nu n_{2-}^\mu}{n_{1-}\cdot n_{2-}} \qquad P_2^{\mu\nu} = g^{\mu\nu} + \frac{n_{1-}\cdot n_{2-}\ n_{3-}^\nu n_{3-}^\mu}{n_{1-}\cdot n_{3-}\ n_{2-}\cdot n_{3-}} - \frac{n_{1-}^\nu n_{3-}^\mu}{n_{1-}\cdot n_{3-}} - \frac{n_{3-}^\nu n_{2-}^\mu}{n_{3-}\cdot n_{2-}}$$

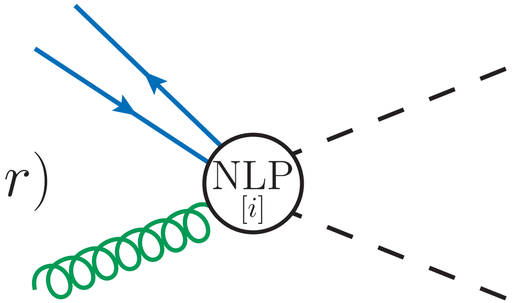
Hard scale $\mu^2 \sim s$

$$\mathcal{M}_{\rm LP}^{\rm QCD} = \frac{i g_s \mathbf{T}^B}{n_{1-}\cdot n_{3-}} \left[\frac{g_W y_t}{2(n_{1+}\cdot q_1)}\right]^2 \frac{1}{r\bar{r}} \Big(\bar{v}_{c_1}(\bar{r}q_1)\frac{\not{n}_{1+}}{2} u_{c_1}(rq_1) n_{3-\nu}\varepsilon_{\perp_1}^{\nu}(q_2) + \bar{v}_{c_1}(\bar{r}q_1)\frac{\not{n}_{1+}}{2}\gamma_5 u_{c_1}(rq_1) n_{3-}^{\mu} i\epsilon_{\mu\nu}^{\perp_1}\varepsilon_{\perp_1}^{\nu}(q_2)\Big)$$

- Considering collinear regions



$$+\ldots = C_{[i]}^{\rm NLP}(s,t;\,r)$$

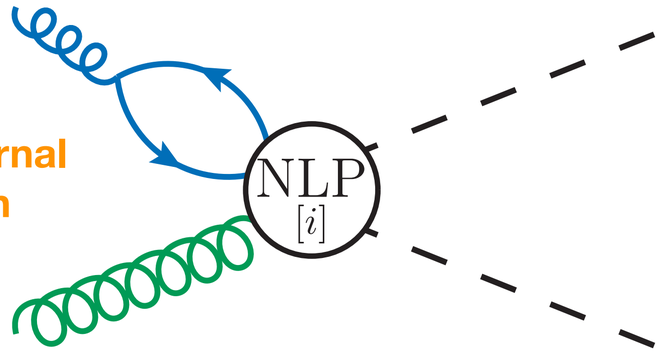


- Relevant operator structures are given by

$$J_{S_i}(\{t_{i_1},t_{i_2}\}) = \bar{\chi}_{c_i}(t_{i_2}n_{i+})\frac{\not{n}_{i+}}{2}\,\chi_{c_i}(t_{i_1}n_{i+}),$$

$$J_{P_i}(\{t_{i_1},t_{i_2}\}) = \bar{\chi}_{c_i}(t_{i_2}n_{i+})\frac{\not{n}_{i+}}{2}\,\gamma_5\,\chi_{c_i}(t_{i_1}n_{i+}),$$

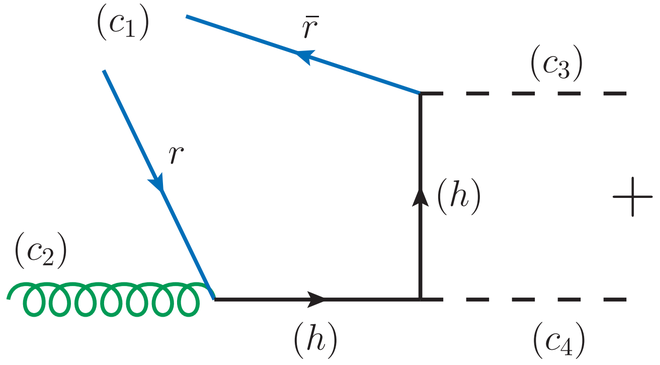
Mixing with the external gluon is forbidden



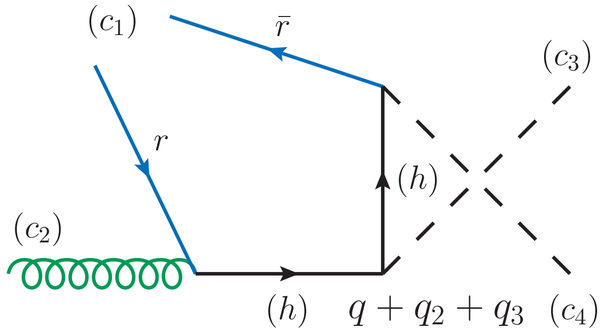
Hard scale $\mu^2 \sim s$

$$\mathcal{M}^{\rm QCD}_{\rm NLP} \sim i g_s \mathbf{T}^B \left[\frac{g_W y_t}{2(n_{1+}\cdot q_1)}\right]^2 \frac{1}{\bar{r}^2 r^2} \frac{(2\,m_t)}{n_{1+}\cdot q_1} \frac{n_{4-}\cdot n_{3-}}{n_{1-}\cdot n_{4-}} \frac{1}{n_{1-}\cdot n_{3-}}$$
$$\times \bar{v}_{c_1}(\bar{q}_1) \frac{\not{n}_{1+}}{2} \gamma_{\perp_1 \nu} u_{c_1}(rq) \varepsilon^{\nu}_{\perp_1}(q_2)$$

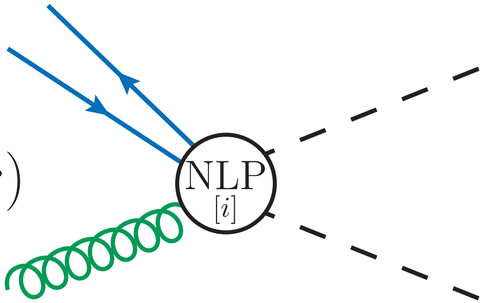
- Considering collinear regions



$+$



$+\ldots = C^{\rm NLP}_{[i]}(s,t;\,r)$

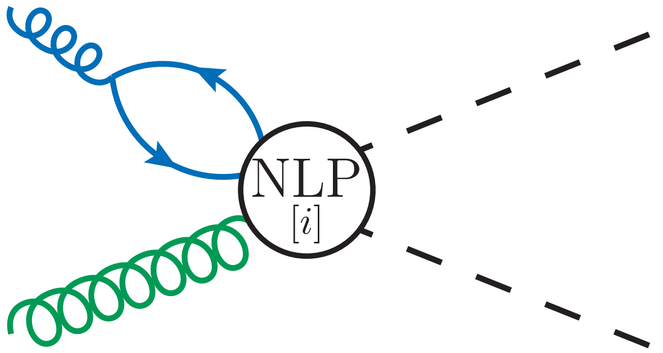


- Now the relevant operator structure is

$$J^{[1]}_{\rm NLP}(\{t_{1_1},t_{1_2}\},t_2,t_3,t_4) = y_t^2\; m_t\; J^{\nu\,A}_{V_1}(\{t_{1_1},t_{1_2}\})\; \mathscr{A}^{c_2\perp_2\,A}_{\nu}(t_2 n_{2+})\; h_{c_3}(t_3 n_{3+})\; h_{c_4}(t_4 n_{4+})$$

with

$$J^{\nu\,A}_{V_i}(\{t_{i_1},t_{i_2}\}) = \bar{\chi}_{c_i}(t_{i_2} n_{i+}) \frac{\not{n}_{i+}}{2}\, \gamma^{\nu}_{\perp_i}\, \mathbf{T}^A\, \chi_{c_i}(t_{i_1} n_{i+})$$

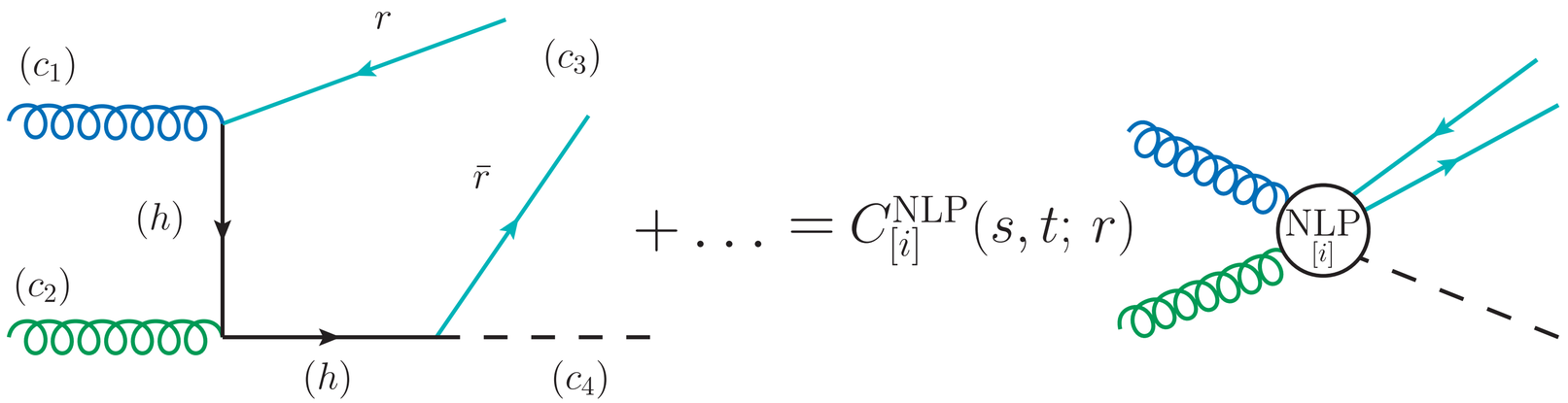


This contribution can mix with the external gluon

Hard scale $\mu^2 \sim s$

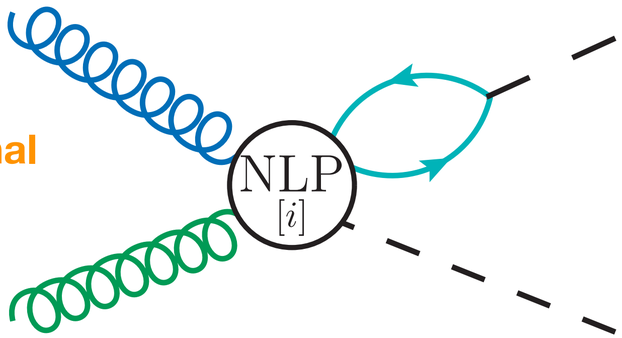
$$\mathcal{M}_{\rm LP}^{\rm QCD} \sim i g_s^2 \mathbf{T}^B \mathbf{T}^A \left[\frac{g_W y_t}{2}\right] \bar{v}_{c_3}(q') \frac{1}{\bar{r}(n_{3+}q_3)} \left[\frac{2n_{3-\mu}}{(n_{1+}q_1)n_{3-}\cdot n_{1-}} \frac{\not{n}_{3+}}{2} \gamma_{\nu\perp_3} u_{c_3}(q) + \frac{1}{r(n_{3+}q_3)} n_{3+\nu} \frac{\not{n}_{3+}}{2} \gamma_{\mu\perp_3} u_{c_3}(q)\right] \varepsilon^{\nu}_{\perp_2}(q_2)\, \varepsilon^{\mu}_{\perp_1}(q_1)$$

- Considering collinear regions



- Here the situation is reversed. The structures appearing at leading power are vector type, which cannot mix with the scalar Higgs boson.

Mixing with the external Higgs is forbidden



Scale $\mu^2 \sim m_t^2$

- We integrate out scale m_t^2: collinear fields are matched to c-PDF modes at LP in $\Lambda^2_{\rm QCD}/s$ expansion

$$\mathscr{J}^{[i]}_{\rm LP}(t_1,t_2) = P^{\mu\nu}_{[i]}\mathscr{A}^{\rm PDF-c_1\perp_1}_{\mu}(t_1 n_{1+})\mathscr{A}^{\rm PDF-c_2\perp_2}_{\nu}(t_2 n_{2+})$$

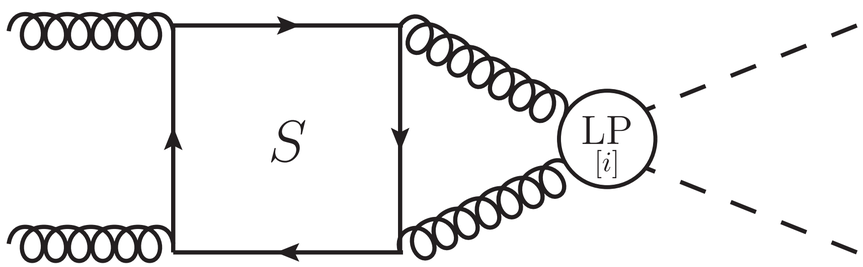
$$\left\langle h(q_3)h(q_4)\right| J^{[i]}_{\rm LP}(0,0,0,0)\left|g(q_1)g(q_2)\right\rangle = C^{[i]}(m_t)\langle 0|\left.\mathscr{J}^{[i]}_{\rm LP}(0,0)\right|g(q_1)g(q_2)\rangle$$

- At the scale m_t^2, the heavy top quarks must be integrated out, their contribution can be obtained from massification [A. Mitov, A. Moch, hep/0612149] [T. Becher, K. Melnikov, 0704.3582] [G. Wang, T. Xia, L. L. Yang, X. Ye, 2312.12242]

$$\left|\mathcal{M}^{\rm massive}(\{p\},\{m\})\right\rangle = \prod_i \left(\mathcal{Z}^{(m|0)}_{[i]}(\{m\})\right)^{1/2} \boldsymbol{\mathcal{S}}(\{p\},\{m\})\left|\mathcal{M}^{\rm massless}(\{p\})\right\rangle$$

$$\mathbf{S}(\{p\},m_t) = 1 + C_A T_f \left(\frac{\alpha_s^{(n_f=6)}}{4\pi}\right)^2 \left(\frac{\mu^2}{m_t^2}\right)^{2\epsilon}\left(-\frac{4}{3\epsilon^2}+\frac{20}{9\epsilon}-\frac{112}{27}-\frac{4\zeta_2}{3}\right)\ln\frac{-s}{m_t^2}$$

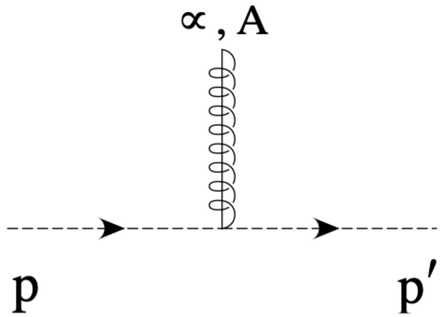
$$C^{[i]}(m_t) = Z^{-1}_{(n_f=5)} Z_{(n_f=6)} \mathscr{Z}^{(m|0)}_g(m_t)\,\mathbf{S}(\{p\},m_t)$$



Summary

- Only the hard region is contributing to the leading power $gg \to hh$ amplitude in the high-energy limit
- The large logarithms in this limit originate from the top-mass counter term
- Checked with expansion-by-regions method up to two-loop amplitudes…
- … and understood in the effective field theory set up.
- The LP and NLP terms give good approximation to the full result in the HE limit ~ 600GeV
- Next steps:
- Resummation + phenomenological impact of higher orders and logs

Auxiliary slides



$$= ig\,T^A \left\{ n^\mu + \frac{\gamma_\perp^\mu \not{p}_\perp}{\bar{n}\cdot p} + \frac{\not{p}'_\perp \gamma_\perp^\mu}{\bar{n}\cdot p'} - \frac{\not{p}'_\perp \not{p}_\perp}{\bar{n}\cdot p\;\bar{n}\cdot p'}\,\bar{n}^\mu \right.$$
$$\left. + \frac{m}{\bar{n}\cdot p\;\bar{n}\cdot p'}\Big[\gamma_\perp^\mu(\bar{n}\cdot p' - \bar{n}\cdot p) + \bar{n}^\mu(\not{p}_\perp - \not{p}'_\perp + m)\Big] \right\} \frac{\not{\bar{n}}}{2}$$

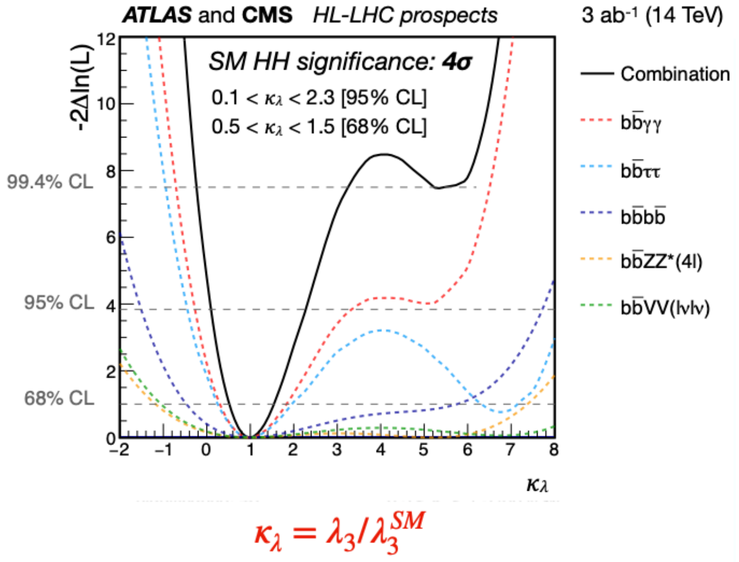
Auxiliary slides

YR18 HL-LHC prospect of Higgs self-coupling

- HH production expected to reach **4.0σ Significance** CMS + ATLAS
- Accessible to Higgs self-coupling: 50% precision from ggHH mode

arXiv:1902.00134

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	



$\kappa_\lambda = \lambda_3/\lambda_3^{SM}$